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ABSTRACT

1.7-40 keV spectra of Cyg X-3 obtained about a year apart using the same rocket payload show large spectral differences. The two observations suggest that while the luminosity of this source remains roughly the same, its spectrum can vary from a featureless blackbody distribution to a flat spectrum which includes strong iron line emission at ~ 6.7 keV. The flux in the line is 0.018 ±0.004 photons $cm^{-2} sec^{-1}$, corresponding to an equivalent continuum width of 1.2 keV.

I. INTRODUCTION

Cyg X-3 is a galactic X-ray source also observed in the infrared and at radio wavelengths. Periodic intensity variations with a period of ~ .2 days imply binary motion in a very compact system. Although its X-ray spectrum apparently does not change over a given binary cycle, there have been reports of long term variability at a few keV (Bleach et al. 1972; Leach et al. 1974) as well as at higher energies (Brisken 1974 and references therein). In this paper we report marked spectral differences observed with the same rocket payload in two flights that took place about a year apart.

II. EXPERIMENT

A payload description as well as other pertinent information concerning the first flight are given in Rothschild et al. (1974) and Holt et al. (1974). A key feature of this payload with regard to X-ray spectra is that two totally independent, but largely identical,

detectors were flown on each occasion. One was filled with a xenon-methane mixture, and the other with argon-methane in similar proportions. This allows consistency checks in the range ~ 1.7 to 20 keV on source spectra inferred from the two sets of data. Both detectors have relatively tight collimation and, since the payload is accurately pointed, we obtain a high source count relative to the background. Spectral information is provided in 128 channels for each detector, covering the energy range up to ~ 20 and ~ 40 keV for the argon and xenon detectors, respectively.

Other payload features of interest to this work include aspect cameras mounted on each of the two detectors, and Fe^{55} sources mounted on the payload doors providing calibration in flight before the doors open as well as after they close.

Information about the two flights is given in Table I. We observed Cyg X-1 and Cyg X-3 on both occasions. The time of the second flight was chosen to give the same phase in the binary cycle for Cyg X-1. As seen in Table I, however, the same time was in chance coincidence with the zero phase of the Cyg X-3 cycle. Although we are primarily concerned in this paper with the Cyg X-3 spectrum, an analysis of the Cyg X-1 data indicates that, to a high statistical significance, the featureless spectra inferred for this source from the two flights and from both detectors were identical. This lends credence to the large spectral differences and structure we have encountered in Cyg X-3 which we report here.

III. ANALYSIS

As we have done on past occasions, we shall present the data in a form that, we believe, best allows for comparisons with other observations. After background subtraction, a numerical incident photon spectrum is inferred from the data using a spectrum-dependent channel-by-channel efficiency that includes the usual considerations, i.e. window transmission, interaction efficiency in the gas, resolution, resonance escape, anticoincidence losses etc. Efficiencies for a best fit to the data are obtained after several iterations in which each new inferred continuum spectrum is the generator of the next set of closer matched efficiencies, etc. All χ^2 calculations to compare an inferred numerical incident spectrum with an analytical spectral form are performed not on individual but on groups of channels, where grouping is designed to 1) maintain a minimum number of net counts in a bin, and 2) establish a bin width comparable to or greater than the resolution of the instrument, thus removing most of the cross coupling between adjacent bins while testing a given source model. If the true incident spectrum contains sharp features such as lines which have not been accounted in the fitting, they will appear broad in the final representation by an amount consistent with counter resolution. To study such features it is best to proceed in the conventional way of folding through the counter response the best fit continuum and the assumed feature(s) and comparing with the data. This hybrid approach is relevant to the 1974 rocket flight where the presence of an emission line in the data is strongly indicated.

IV. RESULTS

In Fig. 1 we present the spectrum for Cyg X-3 obtained from the 1973 flight. We have plotted individual channels where allowed by the statistical accuracy of the data, whereas at higher energies we have used wider energy bins. Also shown in the figure is a fit to the data using a black body spectrum with added absorption by cold interstellar material. This is the only simple spectrum that comes close to giving an acceptable fit below about 10 keV. At higher energies, the observed spectrum becomes harder. We note that, as the statistical accuracy of the data increases, failure to obtain acceptable fits, even when the fitting appears as impressive as in Figure 1, may well be due to small systematic errors resulting from an incomplete knowledge of the detector r sponse functions, particularly near the K absorption edge of argon and the L edges of xenon. Table II summarizes the values of the parameters characterizing the 1973 data. At 10 kpc, we compute an apparent luminosity (1.7 to 40 keV) for the source at $L_x = 8.8 \times 10^{37}$ ergs/sec., whereas the blackbody luminosity at the inferred temperature is 7.2×10^{37} ergs/sec.

Figure 2 shows a radically different spectrum for Cyg X-3 obtained from the 1974 flight. The obvious differences may be summarized as follows:

1. At energies around 4 keV the new spectrum is depleted of photons by about a factor of 10, but at energies above about 15 keV it becomes harder than the 1973 spectrum.

2. The 1974 spectrum shows a strong spectral feature near the energy region where iron K line emission would be expected. Other features may also be present but they do not stand out.

The best fit to these data has been obtained with a thermal continuum including absorption by interstellar material, as well as a narrow emission line. We have used the approximate expression for the Gaunt factor $G(E,kT) \propto (\frac{E}{kT})^{-0.4}$. The best fit to the argon data was obtained for kT = 35 keV and gives $\chi^2 = 5$ for 9 degrees of freedom. Acceptable fits have been obtained for kT $\gtrsim$ 17 keV, a line at 6.71 $\pm$ 0.2 keV and $N_H = 7.0 \pm 1.8 \times 10^{22}$ cm^{-2}. The flux in the line is 0.018 $\pm$ 0.004 photons cm^{-2}sec^{-1} and its equivalent width 1.2 keV. The xenon data could not be successfully fitted but the lowest χ^2 was obtained with kT = 59 keV, a line at 6.62 keV and $N_H = 8.4 \times 10^{22}$ cm^{-2}.

Support for the presence of line(s) in the 1974 spectrum is further provided by Fig. 3 where we show for both counters the residual source counts after subtracting from the data the expected counts obtained from the best fit continua. We have also inserted in the figure, plotted on an arbitrary scale, the Fe^{55} calibration data obtained in flight before as well as after the observation phase. The observed widths in both cases are consistent with being totally due to the resolution of the counters (about 1 keV FWHM at 6 keV). The best fits do indicate sharp lines although upper limits to the intrinsic width have been established at about 1 keV. Failure to obtain acceptable

fits for the xenon data was primarily due to discrepancies around 4 keV where Fig. 3 indicates the possible presence of additional spectral features.

To assure ourselves that the hardening of the spectrum above 15 keV is real and not an artifact of background subtraction we have substituted the xenon background used in the analysis of data from the second flight with the background obtained from the previous flight. There were no discernible changes in the results. We have also checked to insure that all three xenon layers contributed to the higher energy data in the expected proportions, thus ruling out a possible electron contamination of the spectrum that would show only on the first layer.

From the 1974 data we compute an apparent source luminosity $L_x = 4.2 \times 10^{37}$ ergs/sec, over the energy range 1.7 to 40 keV. This is within a factor of 2 of the previous case, although the difference in the total luminosity is probably even smaller because of the harder spectrum.

Splitting the exposure in two segments has shown that, for both flights, no significant spectral changes were taking place during each observation. Furthermore, in both cases the source appeared to have a constant intensity with no evidence of bursting or flickering. Upper limits to periodic fluctuations in the range $\sim$ 2 msec to several seconds were computed at 3 percent for the 1973 flight and 11 percent for the 1974 flight, at the 99 percent confidence level.

For purposes of comparison with other results we have summarized in Table III some customary spectral information.

V. DISCUSSION

The Cyg X-3 spectrum has been know.. to exhibit a turnover at energies as high as 5 keV, suggesting that blackbody emission may provide a plausible interpretation (Gorenstein, Giacconi and Gursky 1967). Bleach et al. (1972), however, found evidence of more complex conditions including the possible presence of spectral features such as absorption edges. The spectra we have presented suggest that a whole range of conditions may exist where the Cyg X-3 spectrum goes from a flat distribution which includes strong iron lines to a featureless black body spectrum.

From UHURU data, Leach et al. (1974) found that the 2-6 keV intensity, averaged over an entire cycle, exhibits states of stable but quite different levels, and that the hardest spectra correspond to times of lowest intensity. Our results from the two flights are consistent with this effect. In addition, we suggest that the detailed spectra we have observed strongly characterize two of these Cyg X-3 states. It is not clear whether the timing of the 1974 observation to coincide with zero phase has special significance as regards the spectrum, or whether the same spectrum would persist throughout the 4.8 hour cycle as implied by the UHURU data. Our projected 2-6 keV UHURU count rate (see Table III), if averaged over a cycle, agrees with the low intensity levels reported by Leach et al. (1974).

The amount of cold matter in the line of sight to the source, implied by the 1973 observation, compares favorably with the lower limit on interstellar material derived from 21 cm emission and absorption profiles, i.e. $N_H = 1.4 \times 10^{22}$ cm^{-2} (Lauqué, Lequeux and Rieu

1972). The significance of the larger absorption deduced from the 1974 data may be questioned in view of the fact that the fitting in this case involved a completely different and more complex spectrum. Since, however, the second observation coincided with zero phase, there may be additional effects which are intrinsic to the geometry of the binary system.

A spectrum that roughly approximates a blackbody distribution with a high energy tail frequently emerges as a likely candidate in models where X-rays are generated from matter accreting onto a compact object (Pringle and Rees 1972; Alme and Wilson 1973). The radiation may originate at the surface of a neutron star heated by the infalling matter or it may result in a thick hot atmosphere surrounding the compact object. Considerable reprocessing of the radiation may result from electron scattering and absorption processes. This may be particularly true in the case of Cyg X-3 where the luminosity is apparently near the Eddington limit.

If blackbody emission at $T \simeq 1.46 \times 10^7$ °K is the correct interpretation of the 1973 spectrum, we calculate a source radius of 1.5×10^6 cm, comparable to that of a neutron star. This indicates that the compact X-ray object is probably smaller than a white dwarf (Davidsen and Ostriker 1974).

Available experimental evidence indicates that most binary sources have flat spectra which steepen or are cut off at the higher energies (Gursky and Schreier 1974; Holt et al. 1974; Ulmer 1975). The Cyg X-3 spectrum from the 1974 observation is consistent with such a picture.

The UHURU data indicate that the Cyg X-3 spectrum remains invariant during the 4.8 hour cycle. Based on the phases of the two observations and the light curves in Leach et al. (1974), the apparent luminosities we have calculated imply that the average luminosity of this source remains constant even when the spectrum has undergone a remarkable change. This behavior might be indicative of a source near the Eddington limit.

Our analysis has shown that the line in the Cyg X-3 spectrum is likely sharp. However, even if the line has an intrinsic width of up to 1 keV, the maximum width consistent with our observation, it still indicates that the optical depth for electron scattering at the source is certainly not much greater than unity (Felten, Rees and Adams 1972). The line appears considerably narrower than that previously reported for Cas A by Serlemitsos et al. (1973) which was interpreted in terms of charge exchange by energetic iron nuclei. If the line is thermally excited, the large equivalent width measured requires iron abundances at the source in excess of two orders of magnitude over the cosmic values.

Another mechanism that can account for strong lines at ~ 6.6 keV from low-ionized iron has been proposed by Basko, Sunyaev, and Titarchuk (1974). They have shown that, in close binary systems, a substantial amount of the primary X-radiation impinging on the normal star is reflected. The reflected component, rich in iron lines, could be the only X-radiation from the binary system reaching an observer who is located outside the primary X-ray beam. It is not clear how would such lines be, at times, totally absent. Furthermore, we do not see how the spectrum could change so drastically while the luminosity remained the same.

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FIGURE CAPTIONS

Figure 1 - Incident X-ray spectrum for Cyg X-3 from flight 13.010 (1973). Solid line is for the best fit blackbody spectrum with added interstellar absorption (see Table II).

Figure 2 - Incident X-ray spectrum for Cyg X-3 from flight 26.037 (1974).

Figure 3 - Residual Cyg X-3 counts (ΔN) after subtracting from the 1974 data the best fit continua. Spectral parameters are given in the text. Also shown on an arbitrary scale are Fe^{55} flight calibrations obtained just before and after the observation.

TABLE I

OBSERVATIONS DURING AEROBEE FLIGHTS 13.010 AND 26.037

SOURCE	τ_d	EPOCH FOR MIN.	13.010 10/4/73 0340 UT JD2441959.65 ϕ	26.037 10/3/74 0510 UT JD2442323.71 ϕ	DURATION OF OBSERVATION (SEC) 13.010	26.037
CYG X-1	5.60096	JD2441992.312 JD2442322.767	0.17±0.06	0.17±0.06	49.6	180.7
CYG X-3	.1996825	JD2441879.016 JD2442078.698	0.81±0.01	0.01±0.02	32.2	18.6
BACKGND.					60.2	39.5

TABLE II

Blackbody Fit To 1973 Data; E<10 keV

	kT(keV)	N_H *	χ^2	f
Argon	1.24 $\pm$.03	2.73 x 10^{22} $\pm$.16	18	7
Xenon	1.24 $\pm$.03	2.58 x 10^{22} $\pm$.15	25	6

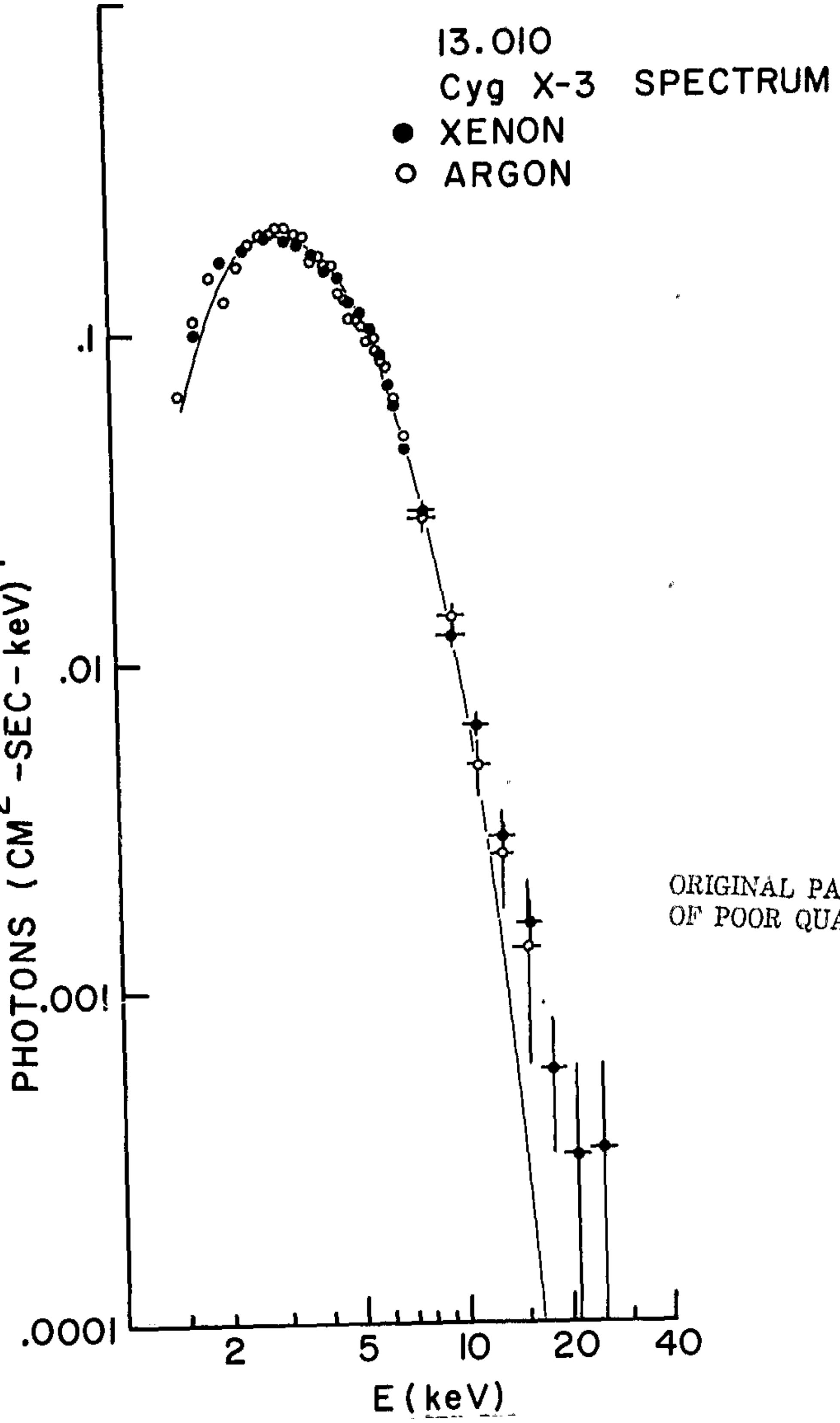
*based on abundances of Brown and Gould (1970).

TABLE III

Cygnus X-3 Flux

	Incident Photon Flux ($cm^{-2}sec^{-1}$)		Incident Energy Flux ($ergs\ cm^{-2}sec^{-1}$)		Expected UHURU Counts sec^{-1}*
Flight 13.010 (1973)	2-6 keV	2-10 keV	2-6 keV	2-10 keV	2-6 keV
Argon	.72	.87	4.3×10^{-9}	6.0×10^{-9}	253
Xenon	.77	.91	4.7×10^{-9}	6.4×10^{-9}	275
Flight 26.037 (1974)					
Argon	.075	.13	5.0×10^{-10}	1.2×10^{-9}	29
Xenon	.070	.12	4.7×10^{-10}	1.1×10^{-9}	28

*Based on conversion factor in Giacconi et al. (1974)


13.010
Cyg X-3 SPECTRUM
XENON
ARGON
PHOTONS (CM^2 -SEC-keV)$^{-1}$
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.01
.001
.0001
2
5
10
20
40
E (keV)

Fig. 1

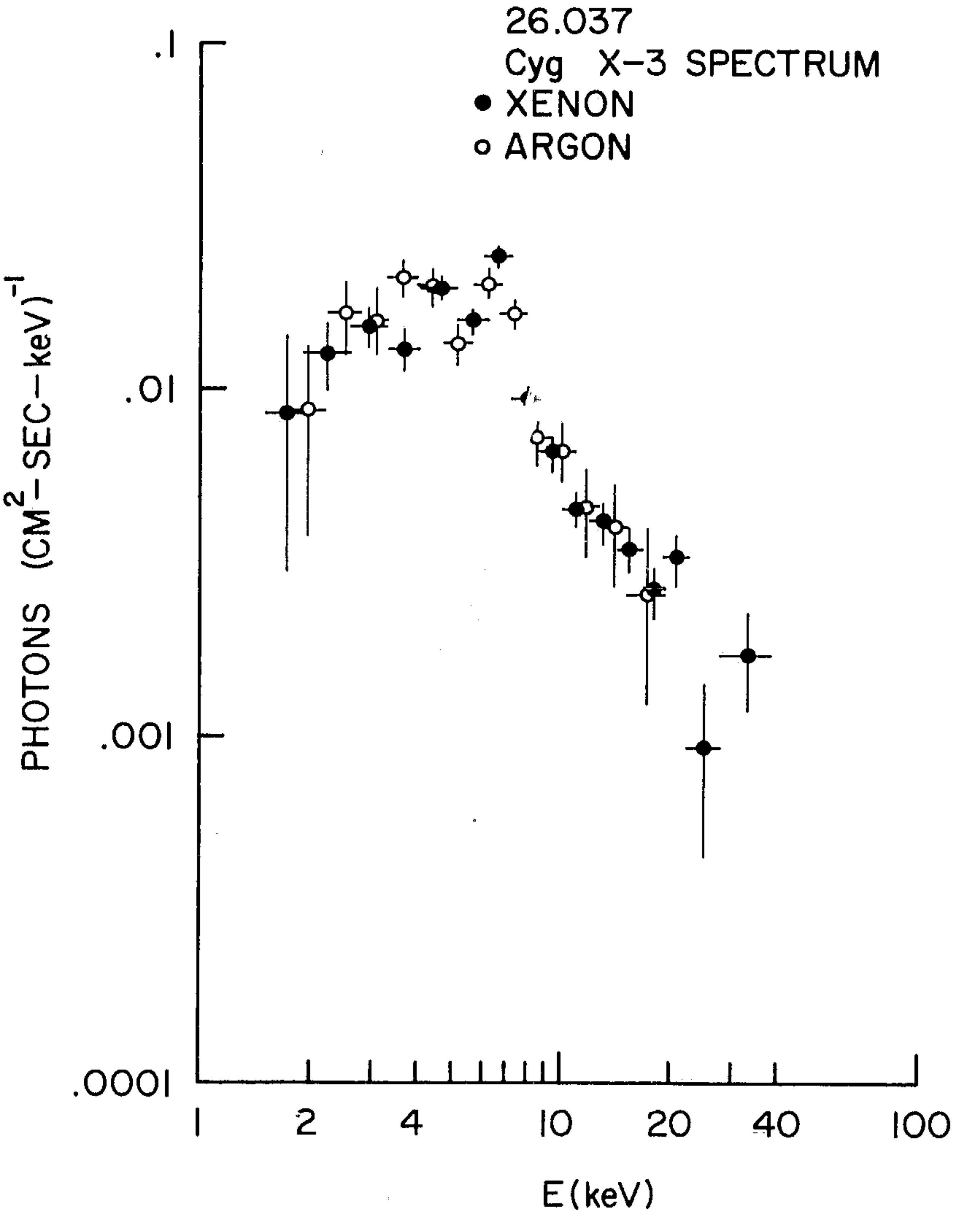
26.037
Cyg X-3 SPECTRUM
● XENON
○ ARGON
PHOTONS $(CM^2-SEC-keV)^{-1}$
.1
.01
.001
.0001
1
2
4
10
20
40
100
E(keV)

Fig. 2

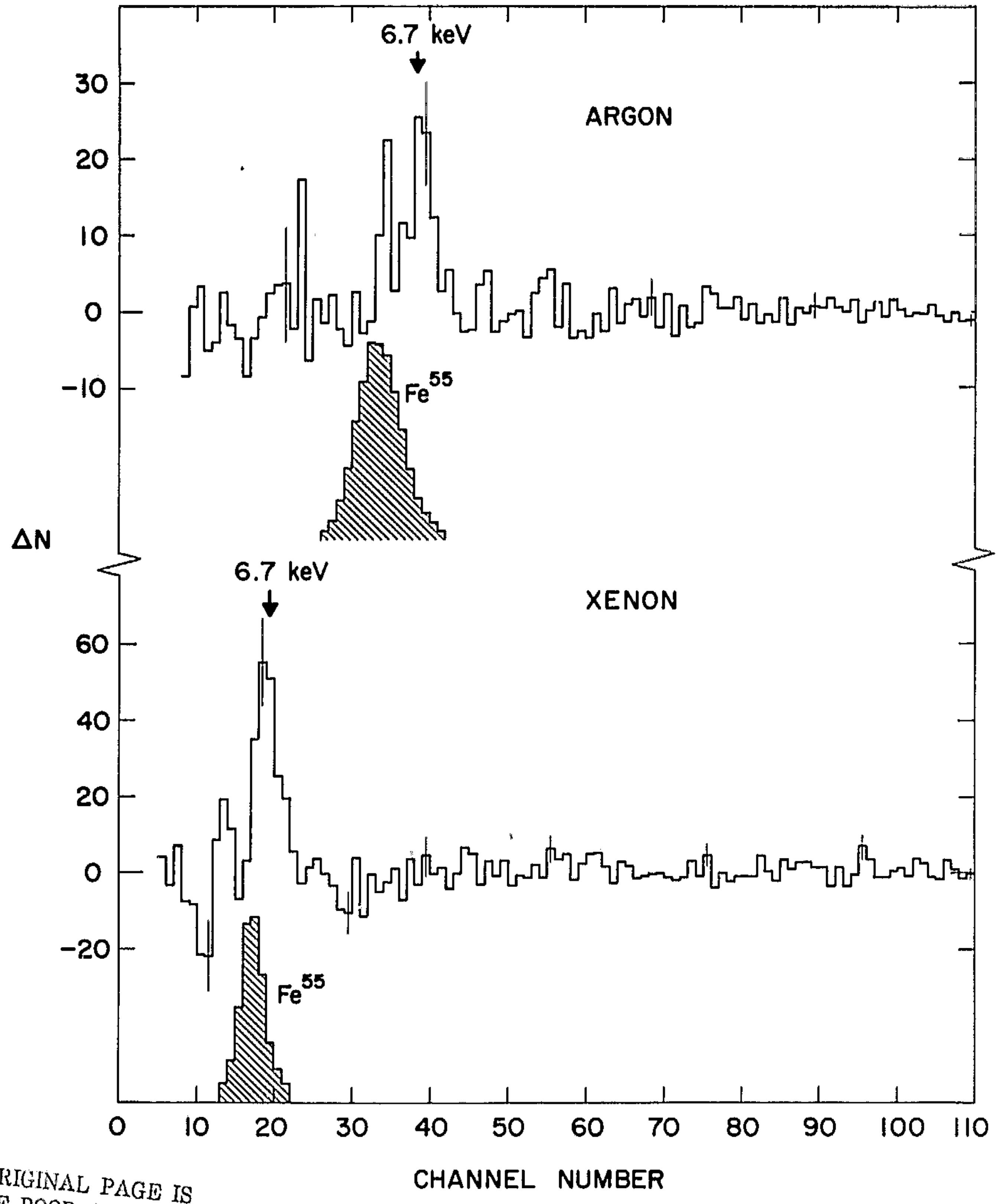

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Fig. 3